US006097699A

United States Patent [19]

Chen et al.

[11] **Patent Number: 6,097,699**

[45] **Date of Patent: Aug. 1, 2000**

[54] **METHOD AND SYSTEM FOR MONITORING BROADBAND QUALITY OF SERVICES**

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[21] Appl. No.: **09/092,605**

[22] Filed: **Jun. 5, 1998**

[51] **Int. Cl.**[7] **G01R 31/08**; G08C 15/00; G06F 11/00

[52] **U.S. Cl.** **370/231**; 370/395

[58] **Field of Search** 370/229, 230, 370/231, 232, 233, 234, 235, 236, 389, 395, 398, 399, 396, 397

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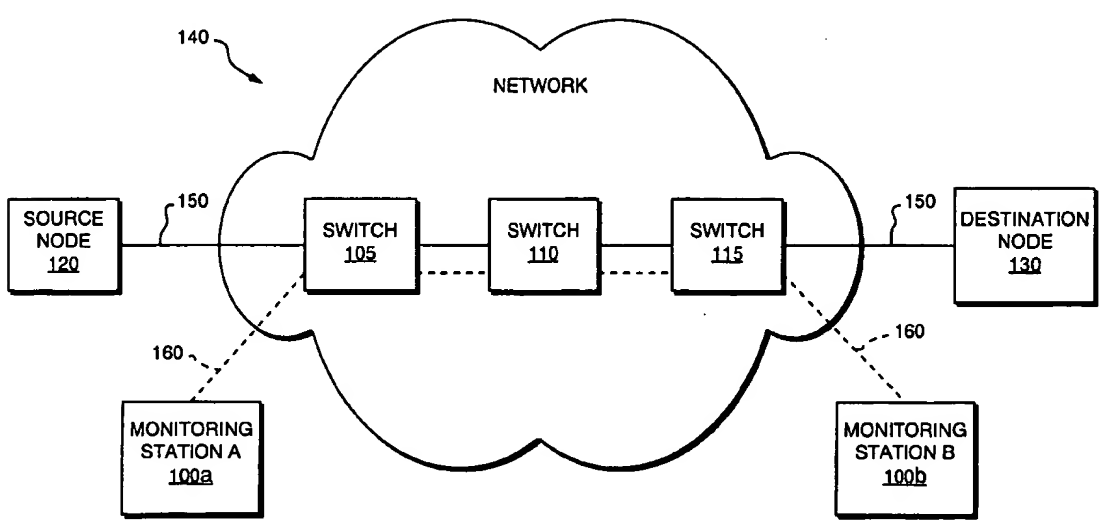
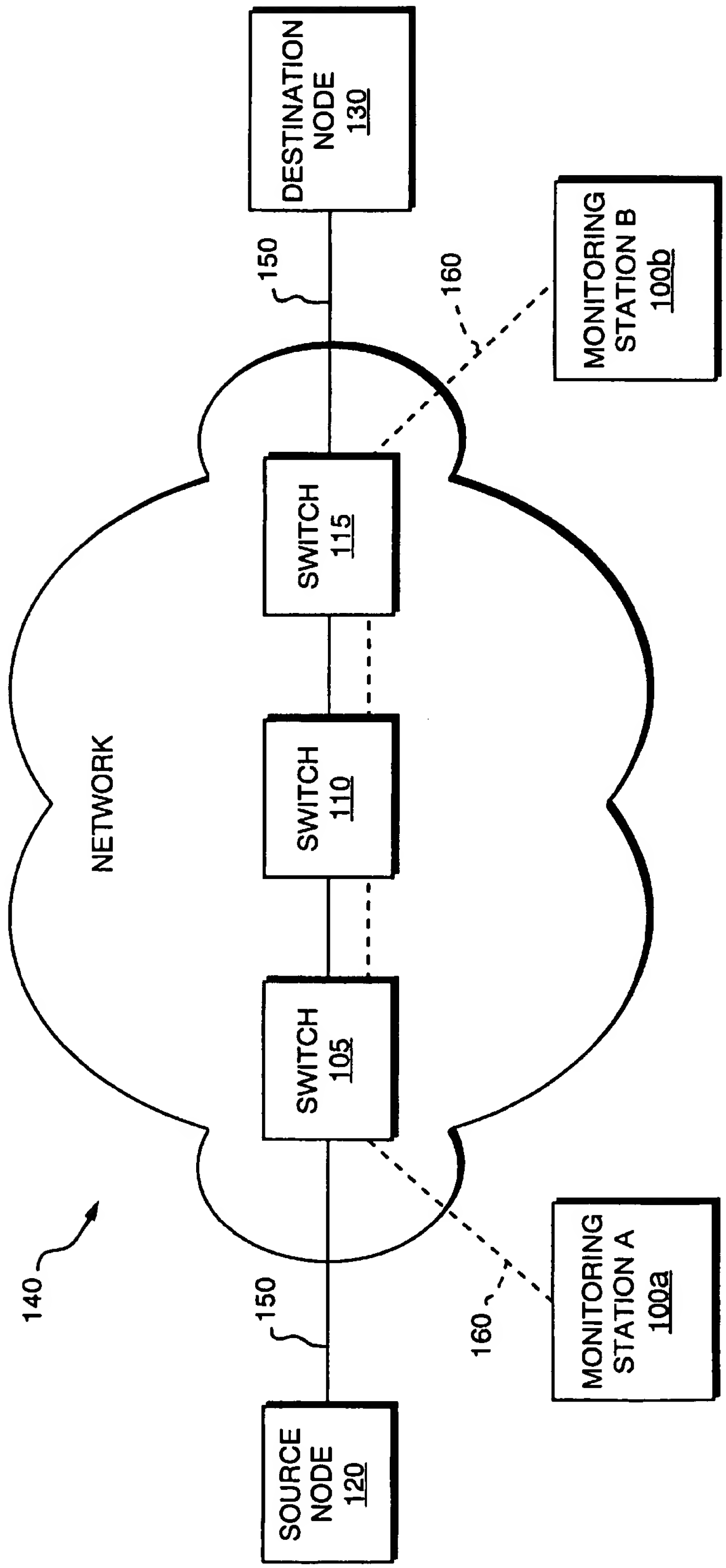
Primary Examiner—Ajit Patel
Assistant Examiner—Bob A. Phunkulh
Attorney, Agent, or Firm—Leonard Charles Suchyta

[57] **ABSTRACT**

A method and system for monitoring a first virtual circuit in an asynchronous transmission mode (ATM) network comprises the steps of establishing in the network a second virtual circuit with the same path and QoS parameters as the first virtual circuit, and monitoring the first virtual circuit by determining the QoS parameters of the second virtual circuit. Specifically, a monitoring station determines the QoS parameters of the second virtual circuit by inserting monitoring information in cells transmitted and received on the second virtual circuit. The monitoring station inserts the monitoring information immediately before transmitting each cell and immediately after receiving each cell. Furthermore, the monitoring station compares the QoS parameters of the second virtual circuit with the QoS parameters of the first virtual circuit to determine network alarm information.

25 Claims, 14 Drawing Sheets

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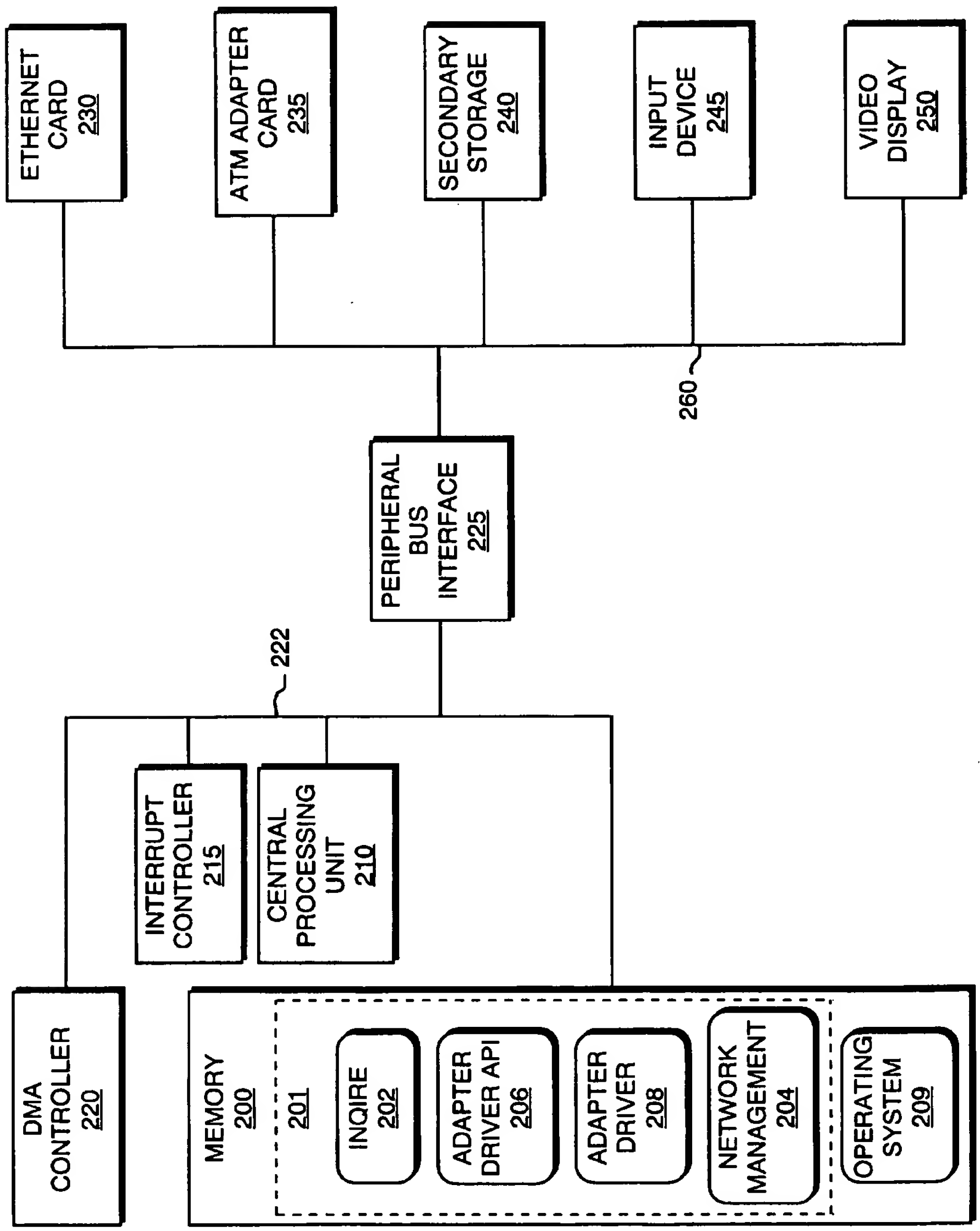
150
160
MONITORING STATION B 100b
SWITCH 115
SWITCH 110
SWITCH 105
NETWORK
140
150
160
MONITORING STATION A 100a
SOURCE NODE 120

FIG. 1

FIG. 2


ETHERNET CARD 230
ATM ADAPTER CARD 235
SECONDARY STORAGE 240
INPUT DEVICE 245
VIDEO DISPLAY 250
260
PERIPHERAL BUS INTERFACE 225
222
INTERRUPT CONTROLLER 215
CENTRAL PROCESSING UNIT 210
DMA CONTROLLER 220
MEMORY 200
201
INQIRE 202
ADAPTER DRIVER API 206
ADAPTER DRIVER 208
NETWORK MANAGEMENT 204
OPERATING SYSTEM 209

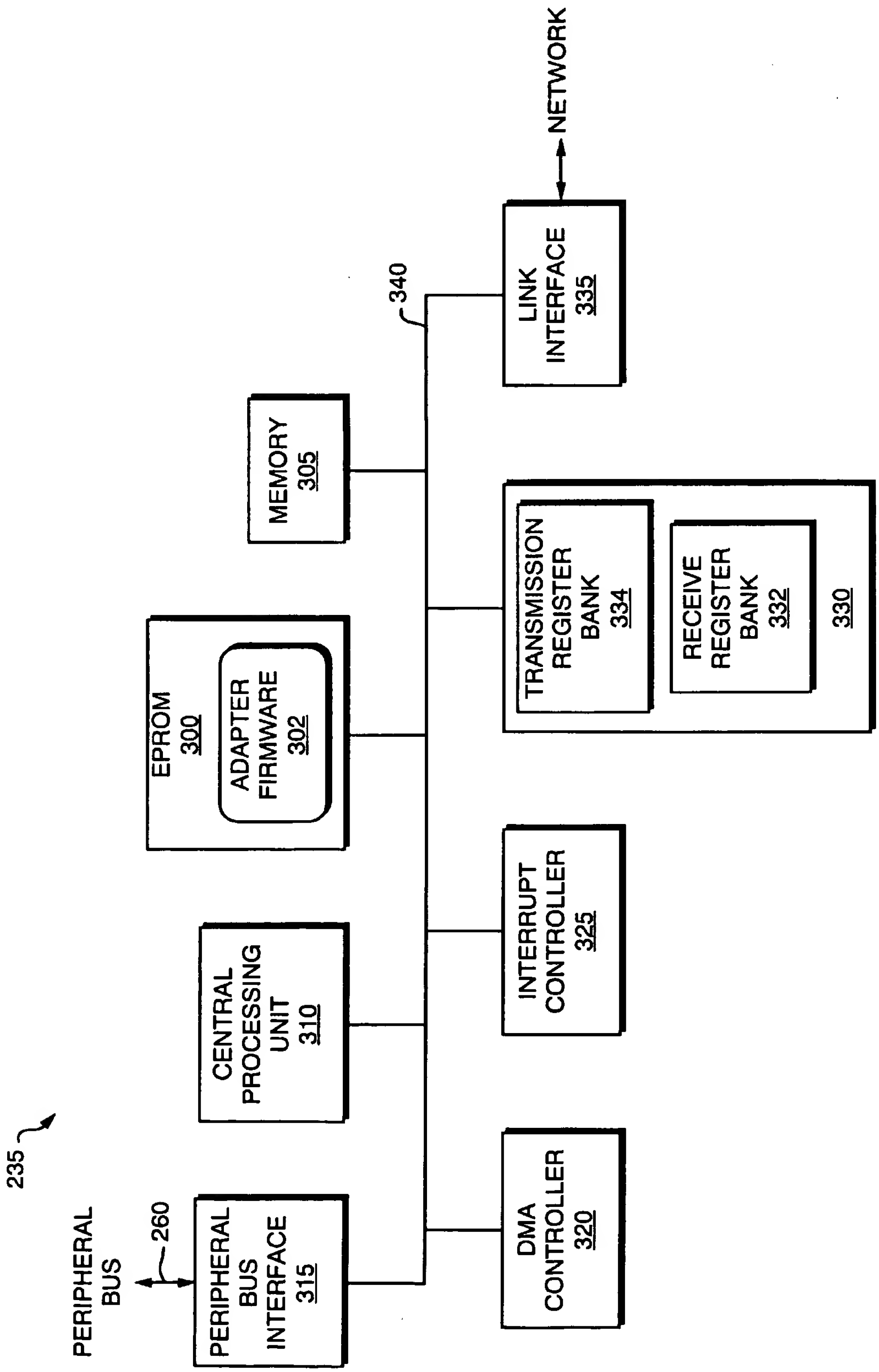

NETWORK
LINK INTERFACE 335
340
MEMORY 305
EPROM 300
ADAPTER FIRMWARE 302
TRANSMISSION REGISTER BANK 334
RECEIVE REGISTER BANK 332
330
CENTRAL PROCESSING UNIT 310
INTERRUPT CONTROLLER 325
235
PERIPHERAL BUS
260
PERIPHERAL BUS INTERFACE 315
DMA CONTROLLER 320

FIG. 3

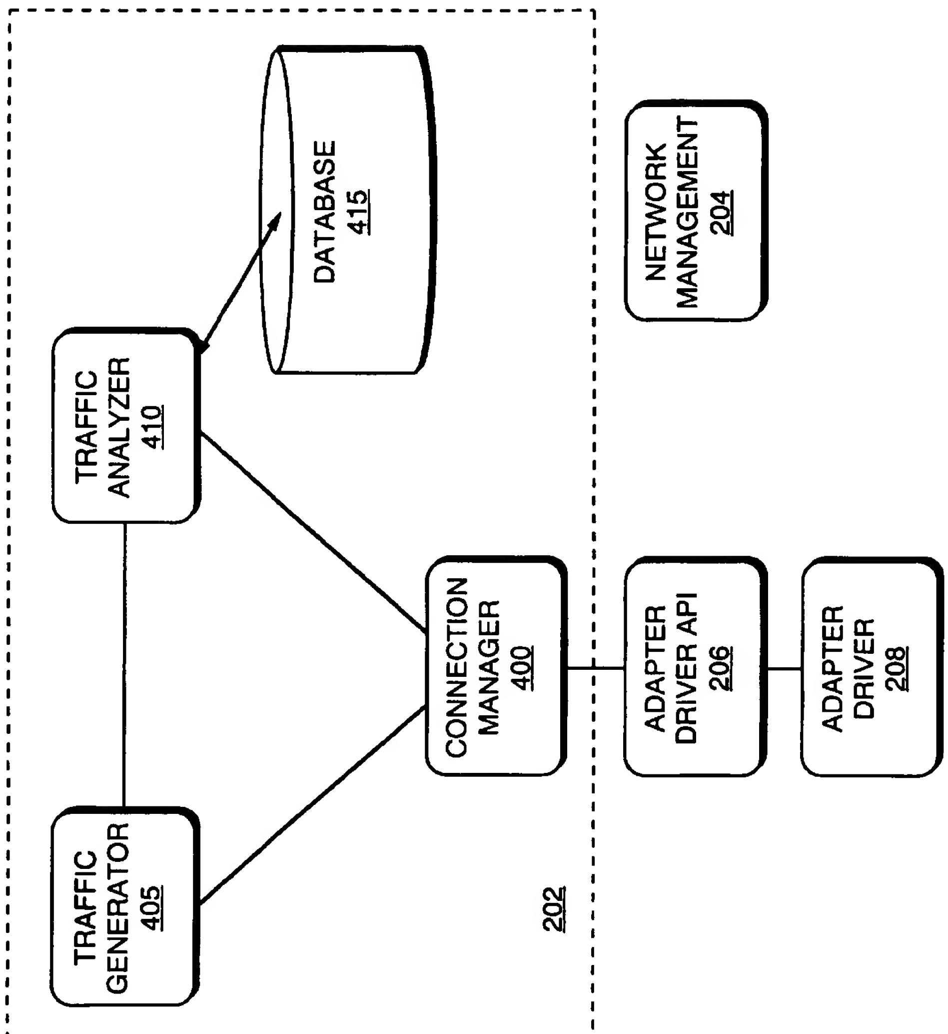

TRAFFIC ANALYZER 410
DATABASE 415
NETWORK MANAGEMENT 204
TRAFFIC GENERATOR 405
CONNECTION MANAGER 400
ADAPTER DRIVER API 206
ADAPTER DRIVER 208
202

FIG. 4

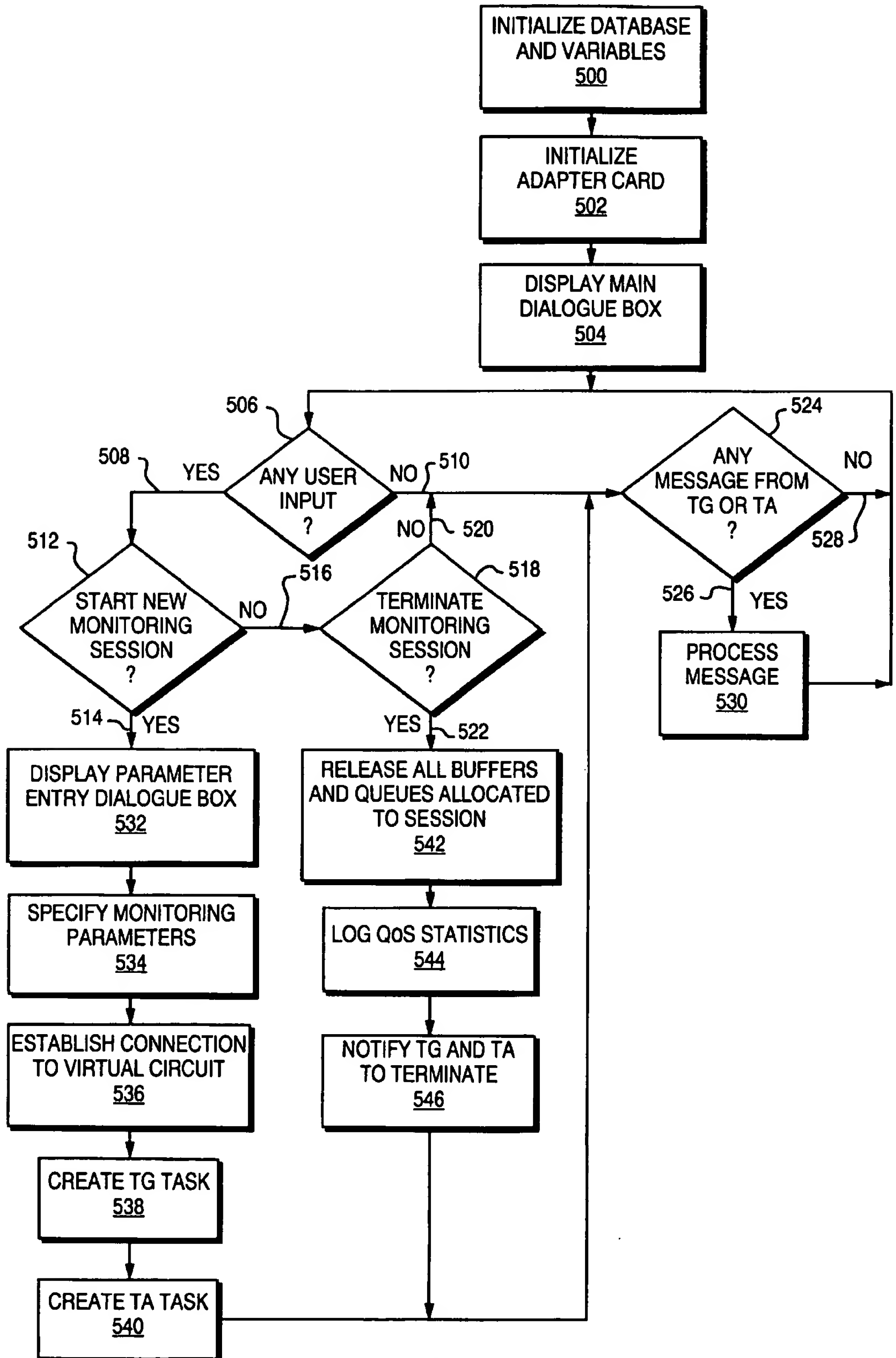

INITIALIZE DATABASE AND VARIABLES 500
INITIALIZE ADAPTER CARD 502
DISPLAY MAIN DIALOGUE BOX 504
506
ANY USER INPUT ?
508
YES
NO
510
524
ANY MESSAGE FROM TG OR TA ?
NO
528
526
YES
PROCESS MESSAGE 530
512
START NEW MONITORING SESSION ?
NO
516
NO
520
518
TERMINATE MONITORING SESSION ?
514
YES
YES
522
DISPLAY PARAMETER ENTRY DIALOGUE BOX 532
SPECIFY MONITORING PARAMETERS 534
ESTABLISH CONNECTION TO VIRTUAL CIRCUIT 536
CREATE TG TASK 538
CREATE TA TASK 540
RELEASE ALL BUFFERS AND QUEUES ALLOCATED TO SESSION 542
LOG QoS STATISTICS 544
NOTIFY TG AND TA TO TERMINATE 546

FIG. 5

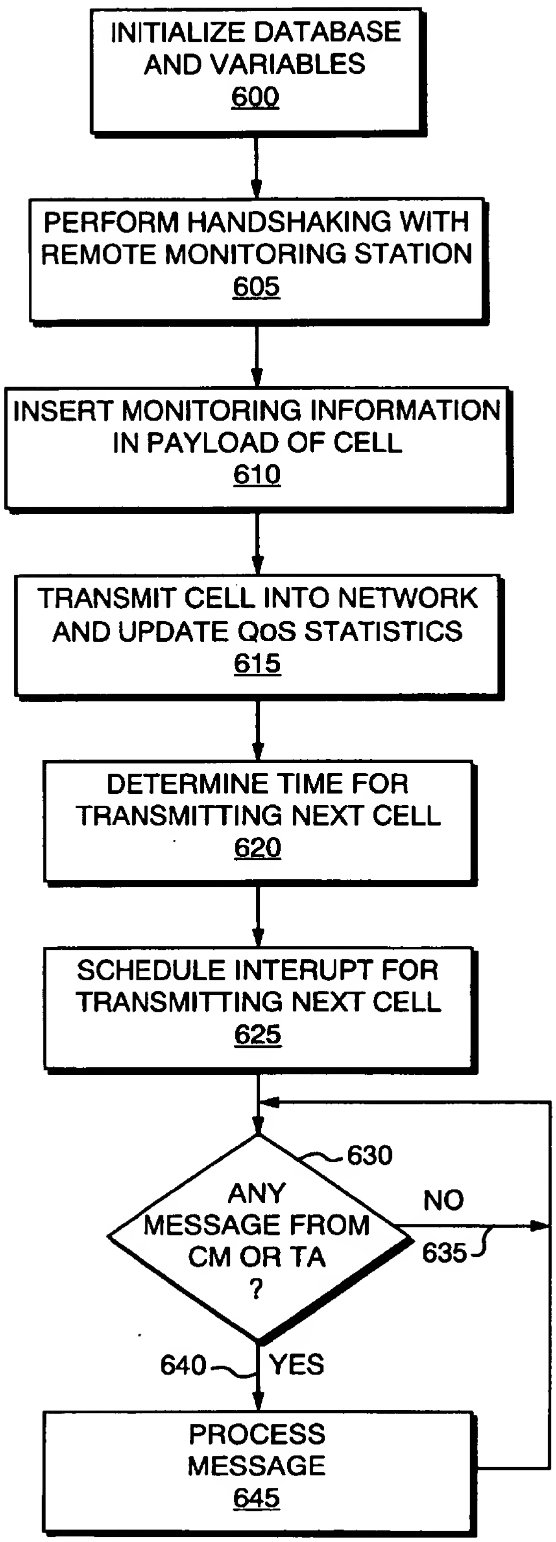

INITIALIZE DATABASE AND VARIABLES 600
PERFORM HANDSHAKING WITH REMOTE MONITORING STATION 605
INSERT MONITORING INFORMATION IN PAYLOAD OF CELL 610
TRANSMIT CELL INTO NETWORK AND UPDATE QoS STATISTICS 615
DETERMINE TIME FOR TRANSMITTING NEXT CELL 620
SCHEDULE INTERUPT FOR TRANSMITTING NEXT CELL 625
630
ANY MESSAGE FROM CM OR TA ?
NO
635
640
YES
PROCESS MESSAGE 645

FIG. 6A

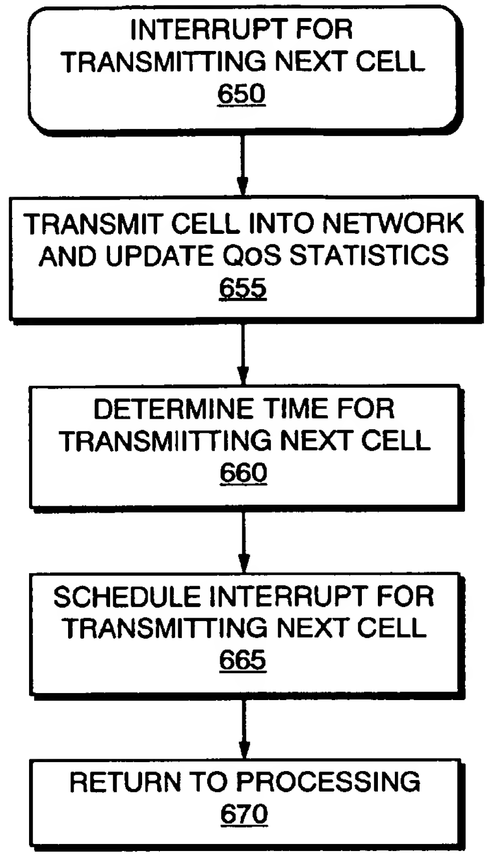

INTERRUPT FOR TRANSMITTING NEXT CELL 650
TRANSMIT CELL INTO NETWORK AND UPDATE QoS STATISTICS 655
DETERMINE TIME FOR TRANSMIITING NEXT CELL 660
SCHEDULE INTERRUPT FOR TRANSMITTING NEXT CELL 665
RETURN TO PROCESSING 670

FIG. 6B

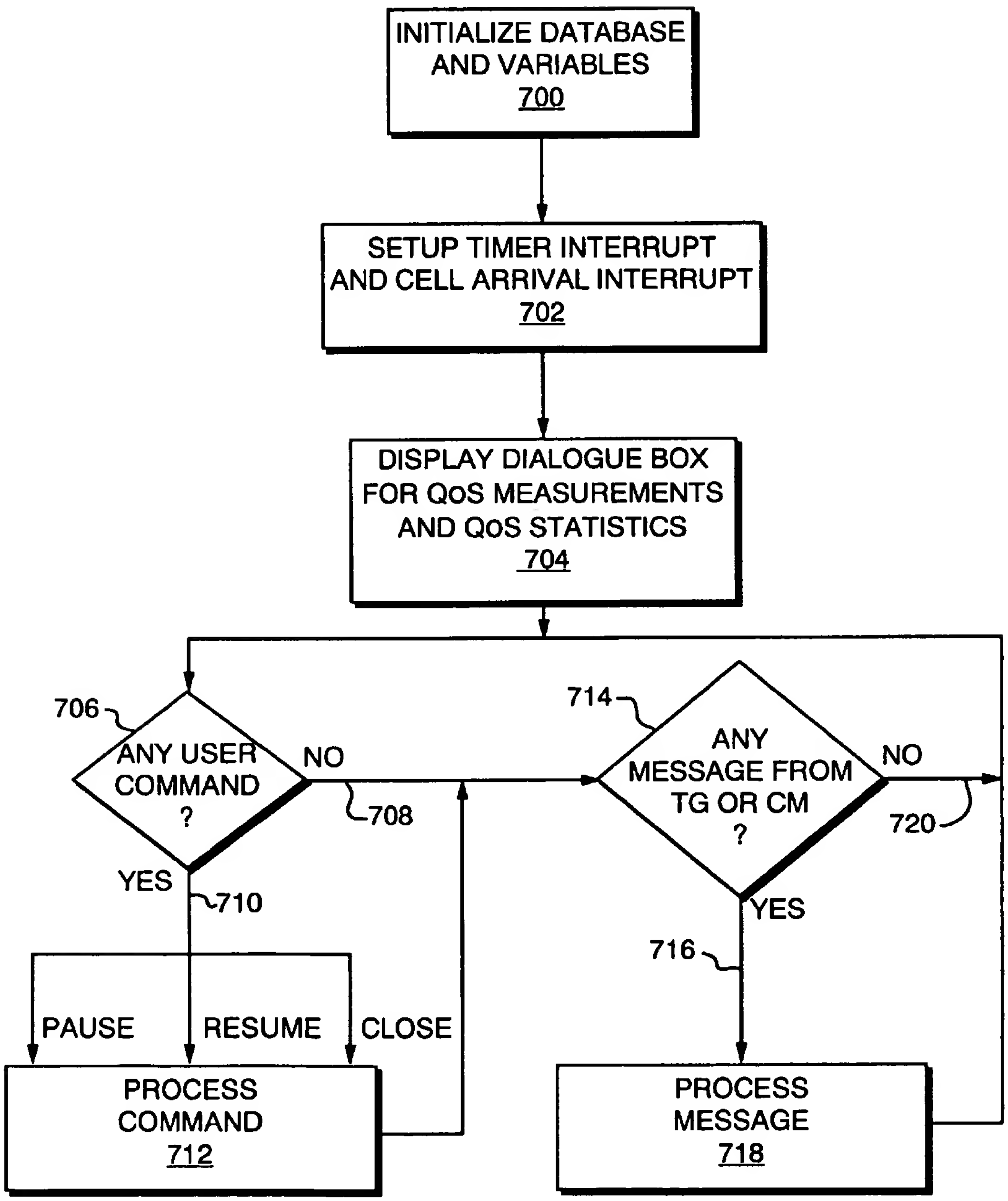

INITIALIZE DATABASE AND VARIABLES 700
SETUP TIMER INTERRUPT AND CELL ARRIVAL INTERRUPT 702
DISPLAY DIALOGUE BOX FOR QoS MEASUREMENTS AND QoS STATISTICS 704
706
ANY USER COMMAND ?
NO
708
YES
710
PAUSE
RESUME
CLOSE
PROCESS COMMAND 712
714
ANY MESSAGE FROM TG OR CM ?
NO
720
YES
716
PROCESS MESSAGE 718

FIG. 7A

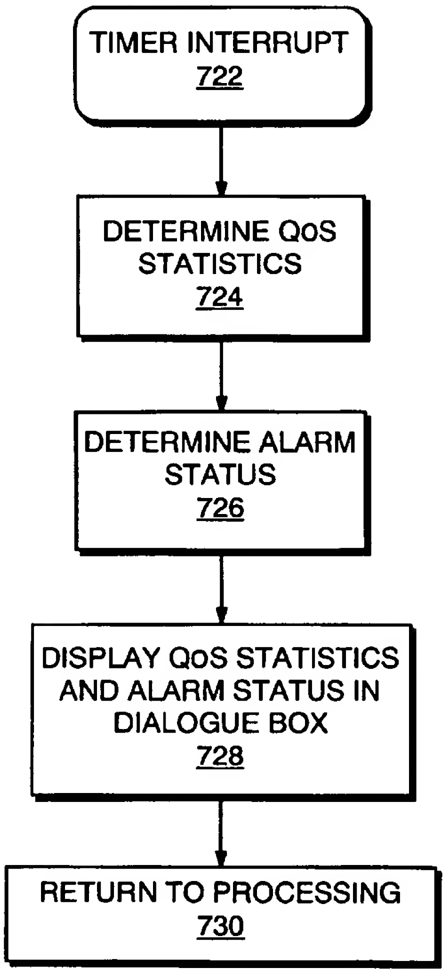

TIMER INTERRUPT 722
DETERMINE QoS STATISTICS 724
DETERMINE ALARM STATUS 726
DISPLAY QoS STATISTICS AND ALARM STATUS IN DIALOGUE BOX 728
RETURN TO PROCESSING 730

FIG. 7B

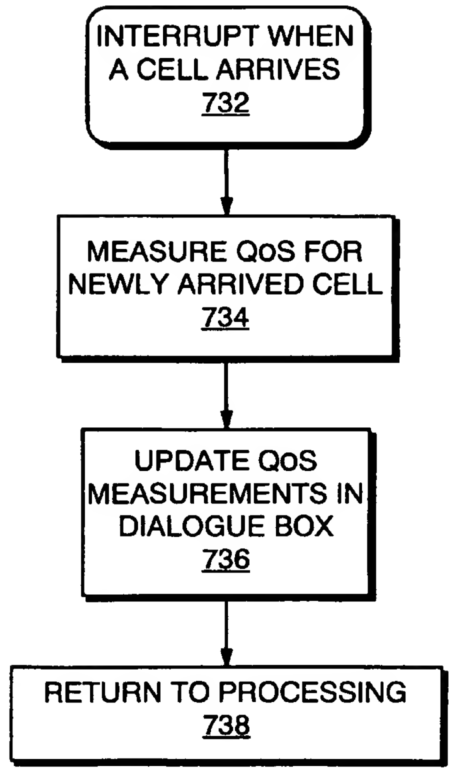

INTERRUPT WHEN A CELL ARRIVES 732
MEASURE QoS FOR NEWLY ARRIVED CELL 734
UPDATE QoS MEASUREMENTS IN DIALOGUE BOX 736
RETURN TO PROCESSING 738

FIG. 7C

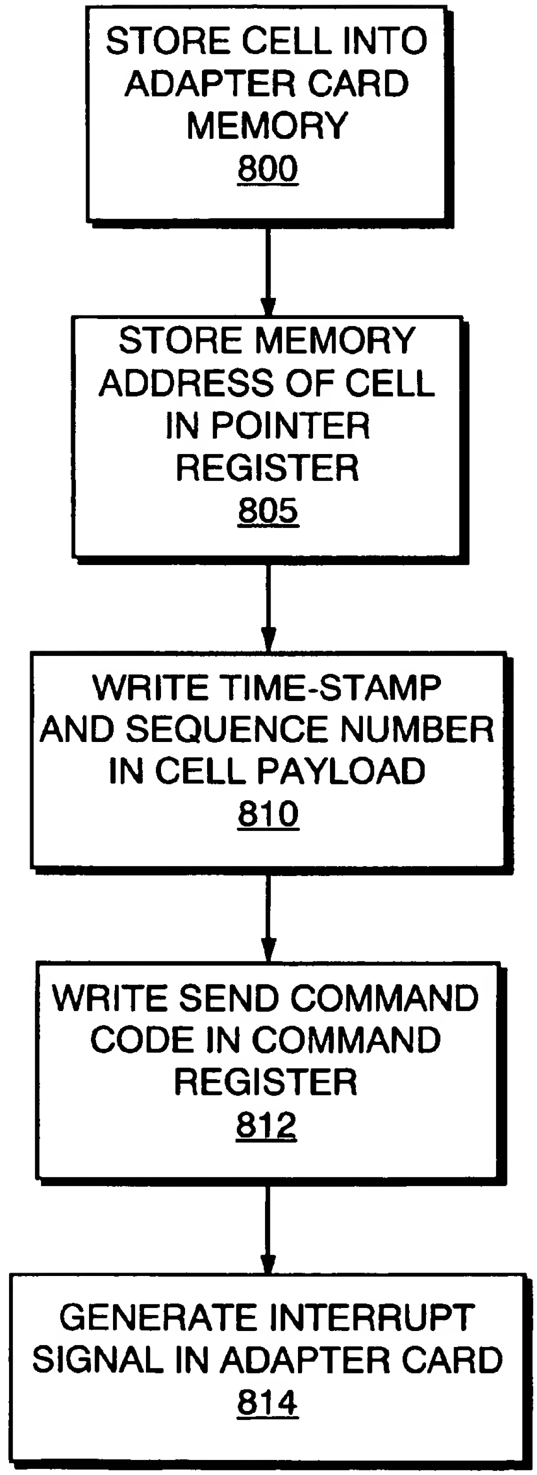

STORE CELL INTO ADAPTER CARD MEMORY 800
STORE MEMORY ADDRESS OF CELL IN POINTER REGISTER 805
WRITE TIME-STAMP AND SEQUENCE NUMBER IN CELL PAYLOAD 810
WRITE SEND COMMAND CODE IN COMMAND REGISTER 812
GENERATE INTERRUPT SIGNAL IN ADAPTER CARD 814

FIG. 8

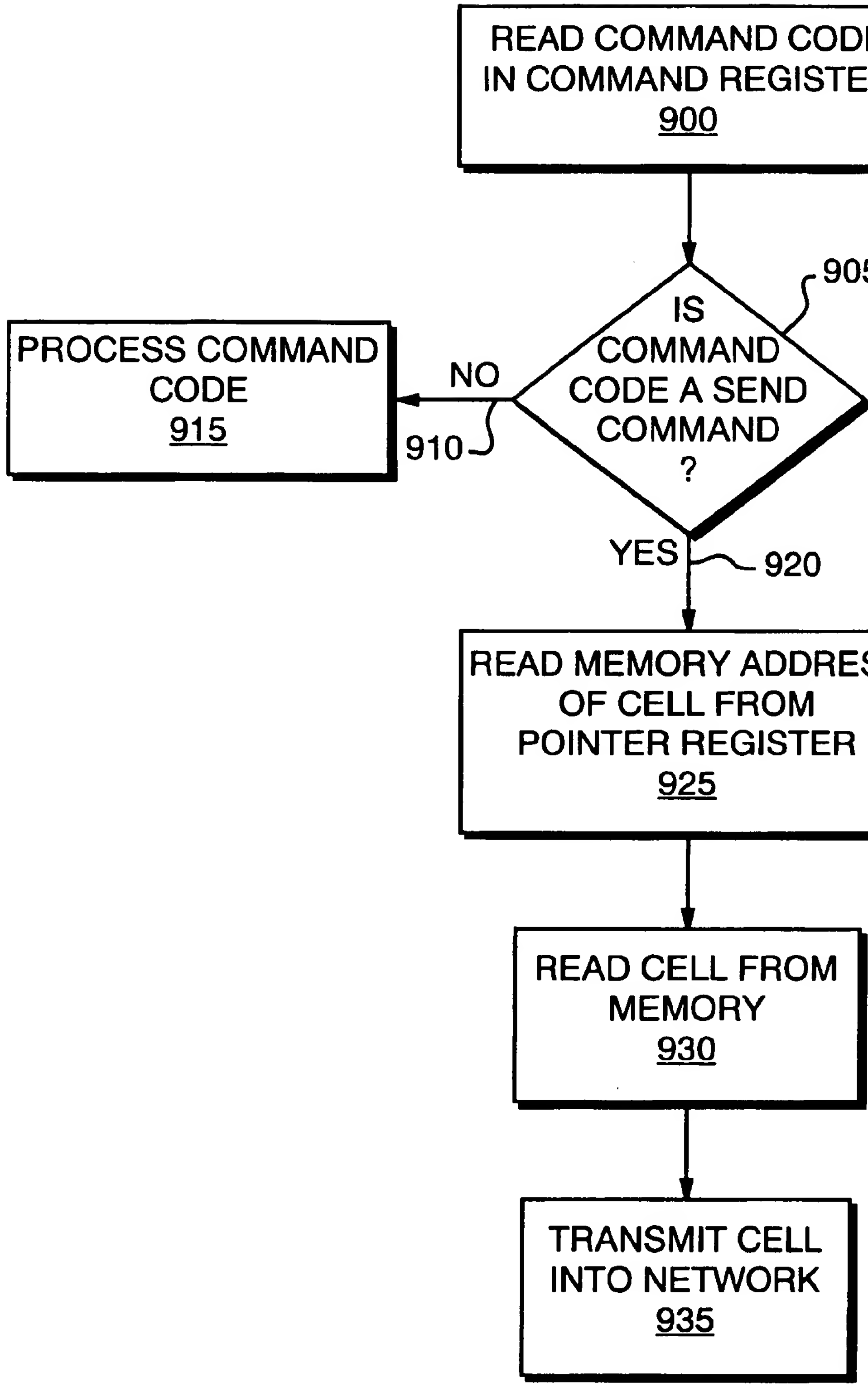

READ COMMAND CODE IN COMMAND REGISTER
900
IS COMMAND CODE A SEND COMMAND ?
905
NO
910
PROCESS COMMAND CODE
915
YES
920
READ MEMORY ADDRESS OF CELL FROM POINTER REGISTER
925
READ CELL FROM MEMORY
930
TRANSMIT CELL INTO NETWORK
935

FIG. 9

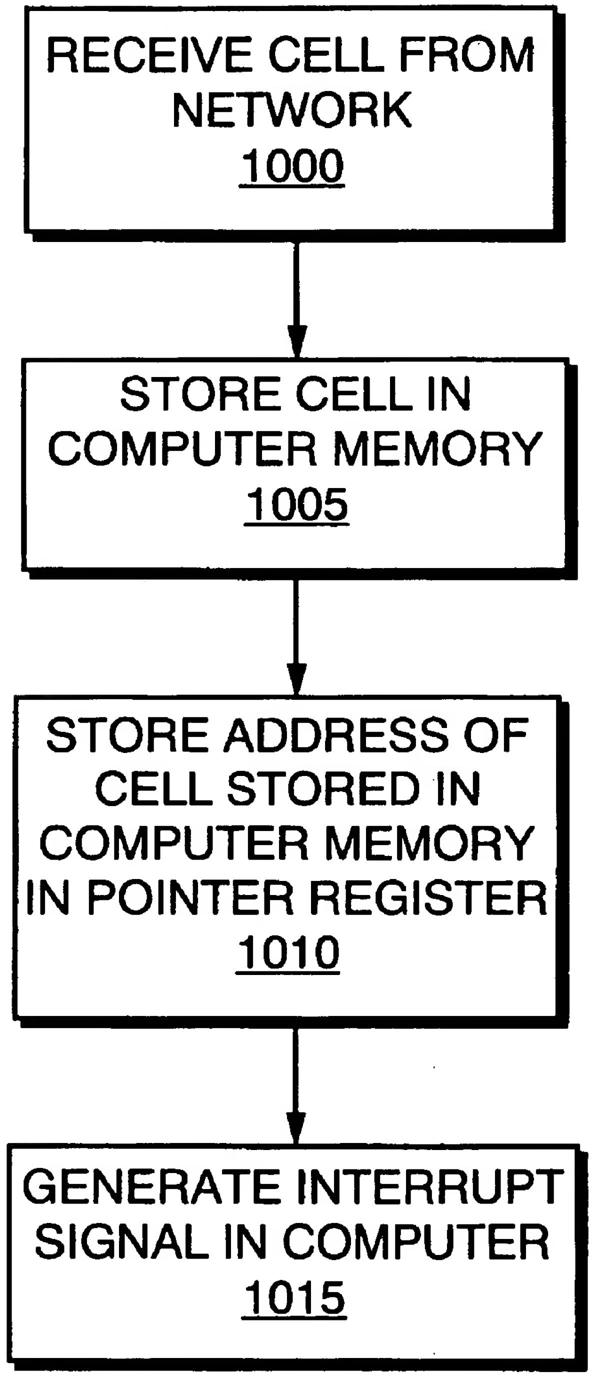

RECEIVE CELL FROM NETWORK
1000
STORE CELL IN COMPUTER MEMORY
1005
STORE ADDRESS OF CELL STORED IN COMPUTER MEMORY IN POINTER REGISTER
1010
GENERATE INTERRUPT SIGNAL IN COMPUTER
1015

FIG. 10

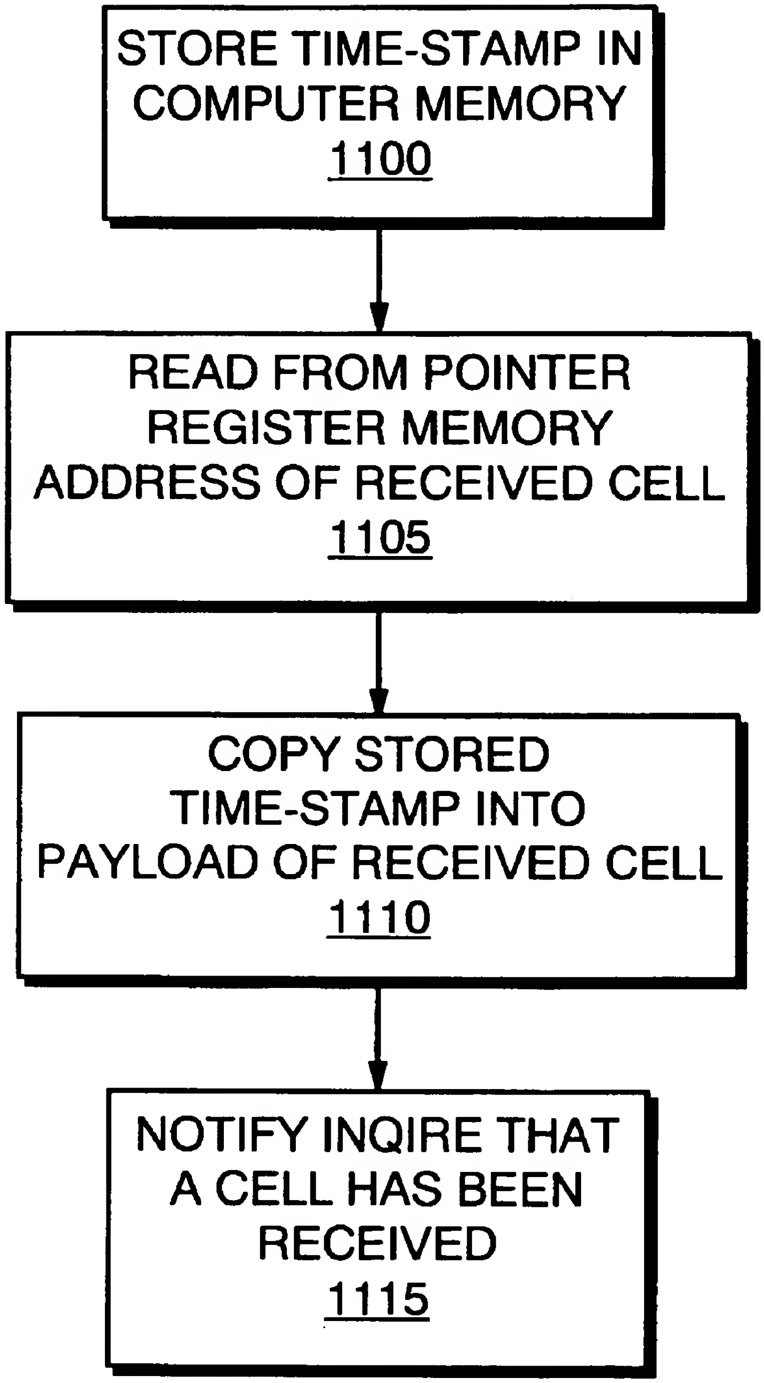

STORE TIME-STAMP IN COMPUTER MEMORY
1100
READ FROM POINTER REGISTER MEMORY ADDRESS OF RECEIVED CELL
1105
COPY STORED TIME-STAMP INTO PAYLOAD OF RECEIVED CELL
1110
NOTIFY INQIRE THAT A CELL HAS BEEN RECEIVED
1115

FIG. 11

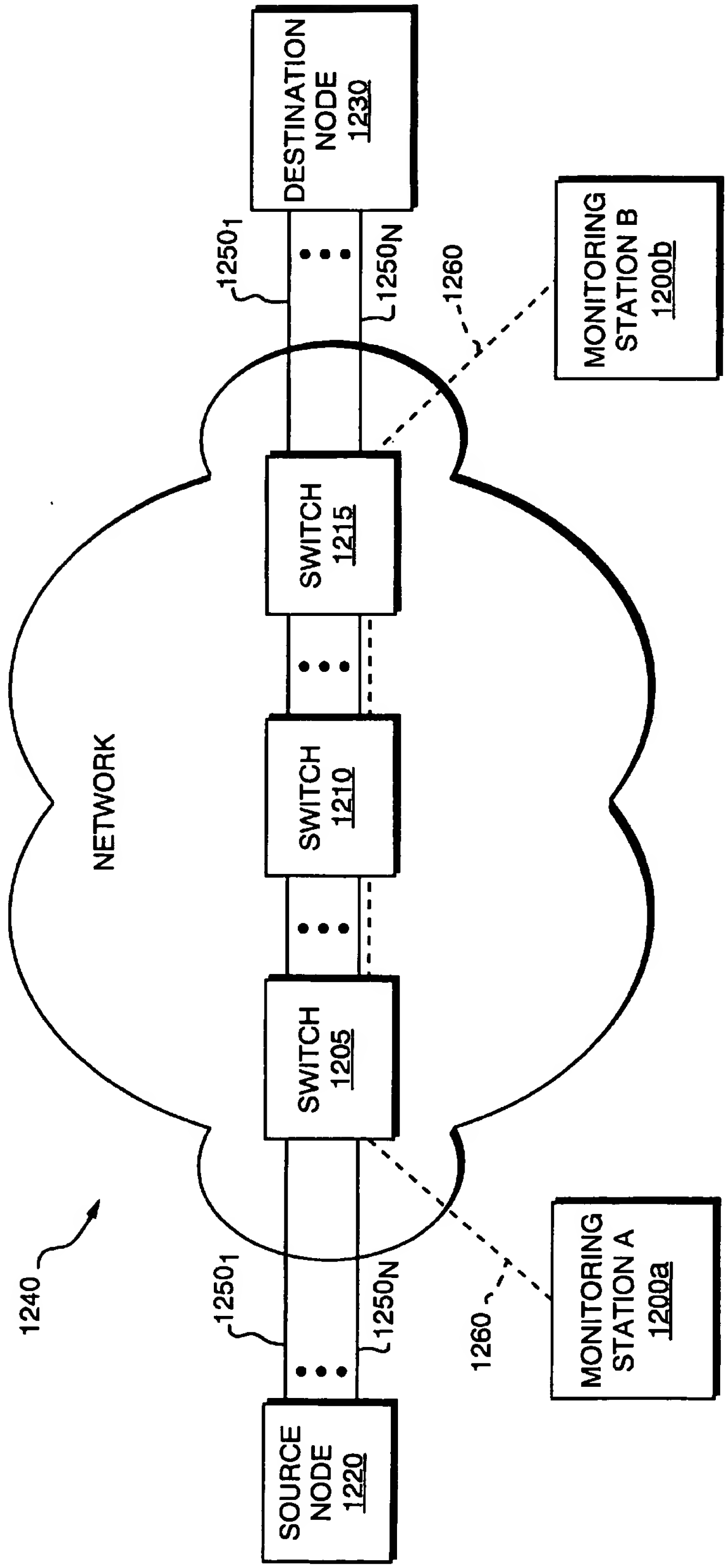

DESTINATION NODE 1230
MONITORING STATION B 1200b
1250_1
1250_N
1260
SWITCH 1215
SWITCH 1210
SWITCH 1205
NETWORK
1240
1250_1
1250_N
1260
MONITORING STATION A 1200a
SOURCE NODE 1220

FIG. 12

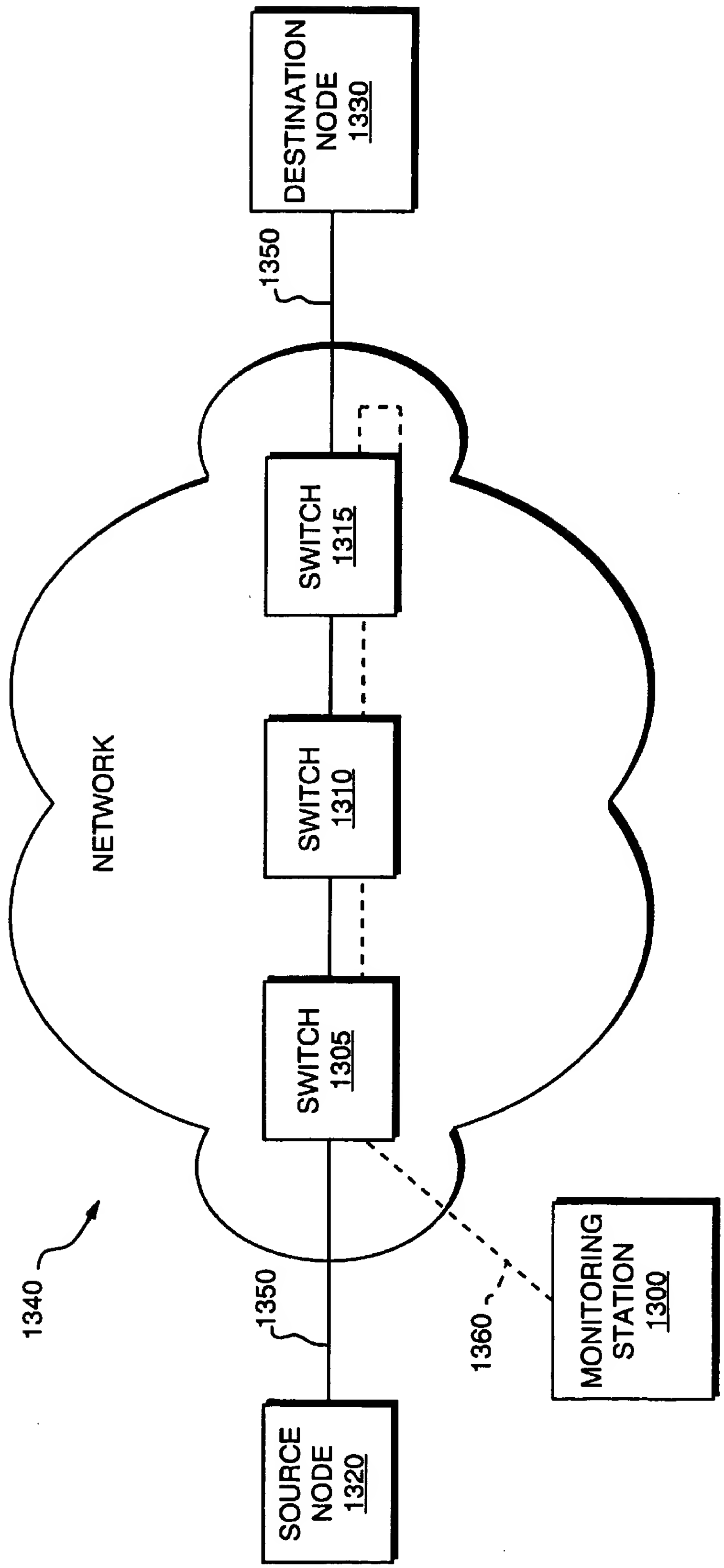

DESTINATION NODE 1330
1350
SWITCH 1315
SWITCH 1310
NETWORK
SWITCH 1305
1340
1350
1360
MONITORING STATION 1300
SOURCE NODE 1320

FIG. 13

METHOD AND SYSTEM FOR MONITORING BROADBAND QUALITY OF SERVICES

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to monitoring of asynchronous transfer mode (ATM) networks, and more particularly, to in-service monitoring of end-to-end Quality of Service (QoS) in ATM networks.

2. Background of the Art

In an ATM network, a user can communicate information with another user through a connection, referred to as a virtual circuit, established in the network. The connection can carry voice, video, and data in fixed-size cells of 53-bytes, which include a 5-byte header and a 48 byte payload field. The connection can support a wide range of services defined by a set of quality of service (QoS) parameters.

The ATM Forum standard, *Traffic Management Specification Version* 4.0, ATM Forum/95-0013R10, February 1996, defines a set of QoS parameters that characterize the end-to-end performance of a connection in an ATM network. When establishing a connection through an ATM network, a user negotiates with the network the set of QoS parameters that characterize the connection. The particular set of QoS parameters depends on the type of service that the user requests from the network. These services include constant bit-rate (CBR), variable bit-rate (VBR), available bit-rate (ABR), and unspecified bit-rate (UBR).

Specifically, through a call admission control procedure, a user signals a request for a new connection in the network, and the network makes a decision to accept or reject the new connection request depending on the specified QoS and the available network resources. Generally, the network accepts a new connection if the network determines that the available network resources will be sufficient to satisfy the specified QoS. If the network accepts the new connection, the network implicitly agrees to a traffic contract that requires the network to sustain the specified QoS as long as the traffic on the connection conforms to the negotiated traffic contract.

The negotiated traffic contract underlaying a connection underscores the need for monitoring and verifying the actual QoS provided by the ATM network. Existing methods for monitoring the QoS in a connection require the users to measure the end-to-end performance of the connection by exchanging monitoring information in the ATM adaptation layer (AAL) or higher protocol layers. For example, users can exchange timing information to measure the end-to-end delay for transmission of cells in a connection.

The existing methods for monitoring the QoS in connections, however, have several disadvantages. First, ATM network switches, routers, and bridges can only access the cell header but not the cell payload. Furthermore, ATM networks cannot use the cell header for performance monitoring because the cell header has been designed to be short and simple to make fast cell switching or relaying possible. Finally, to reduce the processing in ATM switches, an ATM cell has been deliberately designed not to support a cell header field that would include performance monitoring information such as cell sequence numbers and time-stamps.

Second, when performing QoS monitoring, network management systems generally poll ATM switches for performance monitoring information. However, the performance monitoring information collected by the network management systems is generally specific to each switch, and does not include end-to-end QoS monitoring information.

Third, network operators commonly use specialized high-speed testing equipment to test and monitor connections in an ATM network. However, existing testing equipment for broadband networks, such as ATM networks, are typically expensive, complex to use, and intended more for controlled laboratory testing than large scale field application.

ITU-T Rec. 1.610, B-ISDN *Operation and Maintenance Principles and Functions*, Geneva, July 1995, defines a monitoring method, referred to as an operations and maintenance (OAM) method, for in-service performance monitoring in an ATM network. The OAM method inserts OAM cells between blocks of user generated cells. To use the OAM method, ATM switches must recognize the OAM cells and must relay them with the user cells. When a switch that functions as an end-point node receives an OAM cell, the switch processes the OAM cell and inserts its monitoring information in a new OAM cell, which the switch then transmits in the backward direction. Due in part to the additional processing and cell handling complexity associated with the OAM method, most existing ATM switches do not support these capabilities yet.

Furthermore, to reduce costs and integrate network management functions into a single hardware platform, others have attempted to implement monitoring systems for measuring the end-to-end QoS in a connection or a group of connections using a standard computer such as, a personal computer (PC). However, because of the multitasking operating environment of a PC, other tasks such as, user applications, screen savers, disk caching or even mouse movements, may contend with the monitoring system for CPU cycles, and thus, may restrict the accuracy and consistency of monitoring measurements that are time-sensitive.

For example, the monitoring system must time-stamp outgoing cells immediately prior to transmitting the outgoing cells into the network, and similarly, must time-stamp the incoming cells immediately after the monitoring system receives the incoming cells from the network. The resource sharing of the PC's operating system, however, may result in inaccuracies when the monitoring system calculates the time-stamps. Specifically, the monitoring system may not be able to calculate a time-stamp immediately upon arrival of an incoming cell, or may not be able to calculate a time-stamp immediately prior to the transmission of an outgoing cell, in part, because the PC's operating system may have already allocated the current CPU cycles to another task, causing the monitoring system to wait for free CPU cycles.

Thus, it is desirable to have a method and system for in-service monitoring of the end-to-end QoS in a connection or a group of connections in an ATM network without the above-mentioned disadvantages.

SUMMARY OF THE INVENTION

Methods and systems consistent with the present invention, as embodied and broadly described herein, monitor a first virtual circuit in an asynchronous transmission mode (ATM) network by establishing in the network a second virtual circuit with the same path and QoS parameters as the first virtual circuit, and monitoring the first virtual circuit by determining the QoS parameters of the second virtual circuit. Specifically, such methods and systems determine the QoS parameters of the second virtual circuit by inserting monitoring information in cells transmitted on the second virtual circuit. Furthermore, the methods and systems compare the QoS parameters of the second

virtual circuit with the QoS parameters of the first virtual circuit to determine network alarm information.

Methods and systems consistent with the present invention, as embodied and broadly described herein, time-stamp a cell prior to transmission in an ATM network by writing the cell into a memory, writing the current time into the payload field of the cell immediately prior to generating an interrupt signal, and in response to the interrupt signal, transmitting the cell into the network.

Methods and systems consistent with the present invention, as embodied and broadly described herein, time-stamp a cell after receiving the cell from an ATM network by generating an interrupt signal, in response to the interrupt signal storing the current time into a memory, writing the received cell into the memory, and copying the stored time into the payload field of the cell.

Methods and systems consistent with the present invention, as embodied and broadly described herein, have the advantage of accurately and consistently monitoring the end-to-end QoS parameters of a virtual circuit or group of virtual circuits by using a standard PC. In addition, such methods and systems have the advantage of determining QoS parameters of virtual circuits without interrupting service on the virtual circuits, and thus, are non-intrusive and are transparent to network users. Finally, the methods and systems are compatible with any existing ATM network without requiring the implementation of special and expensive functionalities in network switches.

This summary and the following description of the invention should not restrict the scope of the claimed invention. Both provide examples and explanations to enable others to practice the invention. The accompanying drawings, which form part of the description of the invention, show several embodiments of the invention, and together with the description, explain the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In the Figures:

FIG. **1** illustrates a block diagram of a communications network with monitoring stations for monitoring a virtual circuit in accordance with an embodiment of the invention;

FIG. **2** illustrates a block diagram of a monitoring station in accordance with an embodiment of the invention;

FIG. **3** illustrates a block diagram of a network adapter card in accordance with an embodiment of the invention;

FIG. **4** illustrates a block diagram of a monitoring system in accordance with an embodiment of the invention;

FIG. **5** illustrates a flow of chart of the steps that a connection manager in a monitoring system performs in accordance with an embodiment of the invention;

FIGS. *6a* and *6b* illustrate flow charts of the steps that a traffic generator in a monitoring system performs in accordance with an embodiment of the invention;

FIGS. *7a*, *7b*, and *7c* illustrate flow charts of the steps that a traffic analyzer in a monitoring system performs in accordance with an embodiment of the invention;

FIG. **8** illustrates a flow chart of the steps that an adapter driver in a monitoring system performs when transmitting a cell in accordance with an embodiment of the invention;

FIG. **9** illustrates a flow chart of the steps that an adapter card in a monitoring system performs when transmitting a cell in accordance with an embodiment of the invention;

FIG. **10** illustrates a flow chart of the steps that an adapter card in a monitoring system performs when receiving a cell in accordance with an embodiment of the invention;

FIG. **11** illustrates a flow chart of the steps that an adapter driver in a monitoring system performs when receiving a cell in accordance with an embodiment of the invention;

FIG. **12** illustrates a block diagram of a communications network with monitoring stations for monitoring a group of virtual circuits in accordance with an embodiment of the invention; and

FIG. **13** illustrates a block diagram of a communications network with a single monitoring station in accordance with an embodiment of the invention.

DETAILED DESCRIPTION

The following description of embodiments of this invention refers to the accompanying drawings. Where appropriate, the same reference numbers in different drawings refer to the same or similar elements.

Methods and systems consistent with the present invention monitor a first virtual circuit (VC) in an ATM network by establishing in the network a second VC with the same path and quality of service (QoS) parameters as the first VC, and monitoring the first VC by determining the QoS parameters of the second VC. Specifically, a monitoring station determines the QoS parameters of the second VC by inserting monitoring information, for example, a transmission or receive time-stamp and a sequence number, in cells that the monitoring station transmits and receives on the second VC. The monitoring station then compares the QoS parameters of the second VC with the QoS parameters of the first VC to determine network alarm information.

With respect to insertion of monitoring information in cells, an adapter driver program in the monitoring station time-stamps a cell immediately prior to transmitting the cell into the network. Specifically, the adapter driver writes the cell into the memory of a network adapter card and time-stamps the payload field of the cell immediately prior to generating an interrupt signal in the adapter card. In response to the interrupt signal, a firmware in the adapter card then transmits the cell into the network.

The adapter driver program also time-stamps a cell immediately after receiving the cell from the network. Specifically, the adapter card firmware receives the cell from the network and immediately generates an interrupt signal in the monitoring station. In response to the interrupt signal, the adapter driver immediately time-stamps the payload field of the cell.

NETWORK ARCHITECTURE

FIG. **1** illustrates a block diagram of a communications network **140** in accordance with an embodiment of the invention. As shown, network **140** comprises monitoring stations **100A** and **100B**, source node **120**, destination node **130**, and switches **105**, **110**, and **115**. Specifically, source node **120** communicates with destination node **130** through virtual circuit (VC) **150**, which passes through switches **105**, **110**, and **115**. Monitoring station **100A** communicates monitoring information with monitoring station **100B** through virtual circuit (VC) **160**, which has the same path through switches **105**, **110**, and **115** and QoS parameters as VC **150**. Accordingly, monitoring station **100A** may monitor the end-to-end QoS in VC **150** by monitoring the end-to-end QoS in VC **160**.

Monitoring station **100A** inserts monitoring information into the payload of each cell, and transmits the cells on VC **160**. The cells pass through switches **105**, **110**, and **115**, which, for example, may be ATM switches, and arrive at

monitoring station **100B**. Monitoring station **100B** transmits each cell back to monitoring station **100A**. When monitoring station **100A** receives the cells back, monitoring station **100A** measures the end-to-end QoS in VC **150** based on the round-trip transmission time of the cells. Alternatively, in another embodiment, monitoring station **100B** may also insert monitoring information into the payload of the cells before transmitting the cells back to monitoring station **100A**. In this alternate embodiment, monitoring station **100A** can measure the end-to-end QoS in VC **150** based on one-way transmission time of the cells.

FIG. **2** illustrates a block diagram of a monitoring station, for example, monitoring station **100A**, in accordance with an embodiment of the invention. Monitoring station **100A** may include a personal computer (PC), having a memory unit **200**, central processing unit (CPU) **210**, interrupt controller **215**, direct memory access (DMA) controller **220**, high speed bus **222**, peripheral bus interface **225**, peripheral bus **260**, ethernet card **230**, adapter card **235**, secondary storage **240**, input device **245**, and video display **250**. Memory unit **200**, CPU **210**, interrupt controller **215**, and DMA controller **220** interface with each other via high speed bus **222**. Furthermore, memory unit **200**, CPU **210**, interrupt controller **215**, and DMA controller **220** interface with peripheral bus **260**, ethernet card **230**, adapter card **235**, secondary storage **240**, input device **245**, and video display **250** via peripheral bus interface **225**.

Memory unit **200** comprises a monitoring system **201** and operating system **209**, each of which includes a set of instructions that CPU **210** executes. Memory unit **200** may, for example, include a 32 Mbytes random access memory (RAM), and CPU **210** may, for example, include a 200 MHz Pentium processor. Monitoring system **201** includes a monitoring program (INQIRE) **202**, network management program **204**, adapter driver application program interface (API) **206**, and adapter driver **208**. Operating system **209** may include Windows NT® operating system. API **206** may include WinSock2™ software. Both the operating system **209** and API **206** are from Microsoft Corporation.

Secondary storage **240** comprises computer readable medium such as a disk drive and a tape drive. From the tape drive, software and data may be loaded onto the disk drive, which can then be copied into memory unit **200**. Similarly, software and data in memory unit **200** may be copied onto the disk drive, which can then be loaded onto the tape drive.

FIG. **3** illustrates a block diagram of adapter card **235** in accordance with an embodiment of the invention. As shown, adapter card **235** comprises electrically programmable read only memory (EPROM) **300**, memory unit **305**, central processing unit (CPU) **310**, peripheral bus interface **315**, direct memory access (DMA) controller **320**, interrupt controller **325**, register bank **330**, and link interface **335**, all of which interface with adapter bus **340**.

EPROM **300** comprises adapter firmware **302**, which CPU **310** executes. Memory unit **305** comprises data and a set of operating instructions, which CPU **310** also executes. Register bank **330** comprises a transmission (Tx) register bank **334** and a receive (Rx) register bank **332**. Tx register bank **334** and Rx register bank **332** each include a pointer register and a command register. Peripheral bus interface **315** interfaces with peripheral bus **260**. Adapter card **235** interfaces with network **140** via link interface **335**.

FIG. **4** illustrates a block diagram of a monitoring system **201** in accordance with an embodiment of the invention. As shown, monitoring system **201** includes monitoring program network management program **204**, INQIRE **202**, API **206**, and adapter driver **208**. Network management program **204** establishes, maintains, and terminates permanent virtual circuits between any two points in network **140**. Specifically, network management program **204** communicates with switches **105**, **110**, and **115** via ethernet card **230**. Ethernet card **230** may interface with switches **105**, **110**, and **115** via, for example, an Internet Protocol (IP) network (not shown). Network management program **204** may establish VC **160** by sending switch specific commands to each switch **105**, **110**, and **115**, specifying the input port and output port of each switch through which VC **160** must pass. Furthermore, network management program **204** establishes VC **160** with the same path and QoS parameters as VC **150**. Network management program **204** may include switch configuration software, which may be specific to each switch and is generally provided by the particular switch manufacturer.

INQIRE **202** generally transmits and receives cells, determines and analyzes real-time QoS measurements, determines and analyzes QoS statistics, graphically displays the QoS measurement and the QoS statistics, displays alarms for baseline QoS violations, and stores the QoS measurements and the QoS statistics in database **415**. Furthermore, INQIRE **202** invokes adapter driver **208** via API **206** to establish a socket to VC **160** and to insert monitoring information into the payload of each cell transmitted and received on VC **160**. To enhance accuracy of the monitoring information inserted into the payload a cell, high priority may be assigned to INQIRE **202** and adapter driver **208**.

INQIRE **202** includes connection manager (CM) **400**, traffic generator (TG) **405**, traffic analyzer (TA) **410**, and database **415**. CM **400** generally coordinates communications between TA **410** and TG **405**, initiates and terminates monitoring sessions, and handles the main graphical user interface. TG **405** generally composes the payload of outgoing cells and passes the cells to CM **400** for transmission onto network **140**. TA **410** generally determines QoS statistics, analyzes and stores QoS statistics in database **415**, and provides a graphical user interface for displaying QoS statistics and alarms. Flow charts of the steps that CM **400**, TG **405**, and TA **410** each performs will be shown in detail below.

FIG. **5** is a flow of chart of the steps that CM **400** performs in accordance with an embodiment of the invention. CM **400** initializes database **415** and program variables (step **500**). CM **400** then initializes adapter card **235** (step **502**). CM **400** then displays a main dialogue box (step **504**), and prompts the user for input (step **506**).

If the user inputs a request (step **508**), CM **400** then determines whether the user requests a new monitoring session (step **512**). If the user requests a new monitoring session (step **514**) to monitor, for example, VC **150**, which is established between source node **120** and destination node **130** in network **140**, CM **400** displays a dialogue box for inputting monitoring parameters (step **532**).

CM **400** then prompts the user to specify the following monitoring parameters (step **534**): a virtual path identifier (VPI), a virtual circuit identifier (VCI), which identifies, for example, VC **160**, and a set of baseline QoS parameters, which include, for example, cell transfer delay, cell delay variation, and cell loss ratio. The user must specify a VPI and a VCI for VC **160**, which network management program **204** has established with the same path as VC **150**. Similarly, the user must specify the baseline QoS for VC **160** so that the baseline QoS match the negotiated QoS of VC **150**. The user may also specify the starting time, duration, the termination time of the monitoring session, and the rate at which monitoring station **100A** should generate cells on VC **160**.

CM **400** then establishes a connection to VC **160**, which network management program **204** has already established (step **536**). Specifically, CM **400** invokes adapter driver **208** to establish the desired connection via adapter card **235**. CM **400** then creates task TG **405** (step **538**) and task TA **410** (step **540**). Then, CM **400** checks for any messages from TG **405** and TA **410** (step **524**).

If the user does not input a request (step **510**), then CM **400** determines whether there are any messages from TG **405** or TA **410** in inter-process message queues, which are in memory unit **200** (step **524**). If there is a message in any of the inter-process message queues (step **526**), CM **400** processes the message (step **530**). Then, CM **400** checks for more user input, if any (step **506**).

If user inputs a request (step **508**) and the user does not request a new monitoring session (step **516**), CM **400** determines whether the user requests to terminate a monitoring session (step **518**). If the user does not request to terminate a monitoring session (step **520**), CM **400** then checks for any messages from TG **405** and TA **410** (step **524**). If the user requests to terminate a monitoring session (step **522**), CM **400** releases all program buffers and queues allocated to the monitoring session (step **542**). CM **400** then logs to database **415** QoS statistics that are measured in the monitoring session and that are in memory unit **200** (step **544**). Then, CM **400** notifies TG **405** and TA **410** to terminate (step **546**).

FIG. **6*a*** is a flow chart of the steps that TG **405** performs in accordance with an embodiment of the invention. TG **405** initializes database **415** and program variables (step **600**). TG **405** then performs protocol handshaking with remote monitoring station **100B** via VC **160** (step **605**). TG **405** then generates a 48-bytes cell payload, and inserts monitoring information into the payload by invoking adapter driver **208** (step **610**). Specifically, the monitoring information may include, for example, a transmission time-stamp that represents the current time and a sequence number. The steps that adapter driver **208** performs to insert the transmission time-stamp in the payload of the cell are described below in detail.

TG **405** then immediately transmits the cell on VC **160** into network **140**, and updates the QoS statistics for VC **160**, which may, for example, include the total number of cells that TG **405** has transmitted (step **615**). TG **405** then determines the transmission time of the next cell based on the rate of cell transmission, which is specified by the user and is stored in database **415** (step **620**). TG **405** then schedules an interrupt for the transmission of the next cell (step **625**).

TG **405** checks the inter-process message queues for any messages from CM **400** or TA **410** (step **630**). If there is a message in any of the inter-process message queues (step **640**), TG **405** processes the message (step **645**). Then, TG **405** checks for more messages in the queues (step **630**). If there is not a message in any of the queues (step **635**), TG **405** continues to check for messages (step **630**).

FIG. **6*b*** is a flow chart of the steps that TG **405** performs when TG **405** receives an interrupt in accordance with an embodiment of the invention. At any point in time after step **625**, TG **405** may receive an interrupt via interrupt controller **215** to transmit a cell (step **650**). As explained above, TG **405** then generates a cell payload, and inserts monitoring information into the cell payload (step **655**). Specifically, the monitoring information may include, for example, a time-stamp that represents the current time and a sequence number. TG **405** then transmits the cell on VC **160** into network **140**, and updates the QoS statistics for VC **160** in database **415** (step **655**). TG **405** then determines the time for transmitting the next cell based on the rate of cell transmission specified by the user (step **660**). TG **405** then schedules an interrupt for the transmission of the next cell (step **665**). Then, TG **405** returns to the point in processing, at which point TG **405** received the interrupt (step **670**).

FIG. **7*a*** is a flow chart of the steps that TA **410** performs in accordance with an embodiment of the invention. TA **410** initializes database and program variables (step **700**). TA **410** then sets up two interrupts: a timer interrupt and a cell-arrival interrupt (step **702**). Timer interrupt generates an interrupt in CPU **210** in fixed intervals, which may be set to, for example, 100 msec. Cell-arrival interrupt generates an interrupt in CPU **210** whenever adapter card **235** receives a cell from network **140**. As shown below in detail, at a cell-arrival interrupt, TA **410** generally measures the QoS parameters for VC **160** based on the monitoring information in the payloads of the newly arrived cells, and at a timer interrupt, TA **410** generally re-computes the QoS statistics and alarm status for VC **160** based on the measured QoS parameters.

After setting up the timer and cell-arrival interrupts, TA **410** generates a dialogue box for displaying the QoS measurements and QoS statistics (step **704**). Specifically, the QoS measurements displayed may include, for example, cell transfer delay. Cell transfer delay represents the difference between transmission time-stamp and receive time-stamp in the payload of a cell. The QoS statistics displayed in the dialogue box may include, for example, the total number of cells transmitted, the total number of cells received, cell delay variation, cell loss ratio, minimum cell transfer delay, maximum cell transfer delay, and average cell transfer delay, which are specified in ATM Forum, *Traffic Management Specification Version* 4.0, ATM Forum/95-0013R10, Feburary 1996.

FIG. **7*b*** is a flow chart of the steps that TA **410** performs when TA **410** receives a timer interrupt in accordance with an embodiment of the invention. At fixed intervals after step **702**, TA **410** receives a timer interrupt (step **722**). TA **410** then determines QoS statistics for VC **160** as follows (step **724**): TA **410** reads from database **415** the QoS measurements for the last cell that arrived on VC **160**. TA **410** compares the cell transfer delay measured for the last cell with the maximum cell transfer delay and the minimum cell transfer delay stored in database **415**. If the cell transfer delay is greater than the maximum cell transfer delay, TA **410** sets the maximum cell transfer delay to the cell transfer delay of the last cell. If the cell transfer delay is smaller than the minimum cell transfer delay for VC **160**, then TA **410** sets the minimum cell transfer delay to the cell transfer delay of the last cell. Finally, based on the cell transfer delay of the last cell, TA **410** computes a new average cell transfer delay by adding cell transfer delays for each cell that TG **405** transmits and TA **410** receives and dividing the sum by the total number of cells that TA **410** receives.

If TA **410** computes a new maximum cell transfer delay or a minimum cell transfer delay, then TA **410** computes a new cell delay variation by subtracting the minimum cell transfer delay from the maximum cell transfer delay. TA 410 then computes a new cell loss ratio as follows: TA **410** increments a cell-loss counter by subtracting the sequence number of a newly arrived cell from the sequence number of the previous cell that TA **410** received minus 1. TA **410** then divides the content of the cell-loss counter by the sequence number of the newly arrived cell. Finally, TA **410** stores the newly computed QoS statistics in database **415**.

TA **410** determines alarm status information for VC **160** by comparing the QoS statistics determined in step **724** with

the baseline QoS parameters for VC **160** as follows (step **726**): TA **410** reads from database **415** the baseline QoS parameters, which may include, for example, average cell transfer delay, cell delay variation, and cell loss ratio. If TA **410** determines that any of the QoS statistics for VC **160** exceeds any of the baseline QoS parameters, TA **410** updates the alarm information, which TA **410** stores as the difference between the QoS statistics and the baseline QoS. Finally, TA **410** displays the newly computed QoS statistics and alarm status information in the dialogue box for displaying QoS statistics and QoS measurements (step **728**). Then, TA **410** returns to the point in processing where TA **410** received the timer interrupt (step **730**).

FIG. **7c** is a flow chart of the steps that TA **410** performs when TA **410** receives a cell-arrival interrupt in accordance with an embodiment of the invention. When a cell arrives at adapter card **235**, interrupt controller **325** generates an interrupt in CPU **210**, causing adapter driver **208** to insert a receive time-stamp in the payload of the newly received cell (step **732**). The steps that adapter driver **208** performs to insert a receive time-stamp into the payload of a newly received cell are described below in detail.

TA **410** then measures the QoS for VC **160** based on the time-stamp and sequence number information in the payload of the cell as follows (step **734**): TA **410** reads the sequence number, the transmission time-stamp, and the receive time-stamp from payload of the cell. TA **410** computes the cell transfer delay for that cell by subtracting the transmission time-stamp from the receive time-stamp, stores the result in database **415**, and displays the result in the previously generated dialogue box (step **736**). Then, TA **410** returns to the point in processing at which point TA **410** received the cell-arrival interrupt (step **738**).

The flow charts of FIGS. **8** through **11** collectively describe the steps that adapter driver **208** and adapter firmware **302** may perform when time-stamping ATM cells in accordance with an embodiment of the invention. However, in an alternative embodiment, a monitoring station may generally perform these same steps to time-stamp packets when transmitting and receiving packets in a communications network other than an ATM network. For example, a monitoring station may perform the steps of FIGS. **8** through **11** described below to time-stamp packets for monitoring the performance of a packet-switched communications network.

FIG. **8** is a flow chart of the steps that adapter driver **208** performs when transmitting a cell in accordance with an embodiment of the invention. Adapter driver **208** stores the cell in adapter card memory **305** (step **800**), and stores the address of the cell in the pointer register of Tx register bank **334** (step **805**). Adapter driver **208** inserts a time-stamp and a sequence number in the payload of the cell (step **810**). Adapter driver **208** then writes a SEND command into the command register of Tx register bank **334** (step **812**), which triggers interrupt controller **325** to generate a hardware interrupt in adapter card **235** (step **814**).

FIG. **9** is a flow chart of the steps that adapter card **235** performs when interrupt controller **325** generates a hardware interrupt in adapter card **235** in accordance with an embodiment of the invention. Adapter firmware **302** reads the command code in command register of Tx register bank **334**. Adapter firmware **302** determines whether the command code is a SEND command (step **905**). If the command code is not a SEND command (step **910**), adapter firmware **302** processes the command code (step **915**).

If the command code is a SEND command (step **920**), adapter firmware **302** reads the address of the cell stored in

adapter card memory **305** from the pointer register of Tx register bank **334** (step **925**). Adapter firmware **302** then instructs DMA controller **320** to read the cell from adapter card memory **305** (step **930**) and to transmit the cell via link interface **335** to network **140** (step **935**).

FIG. **10** is a flow chart of the steps that adapter card **235** performs when adapter card **235** receives a cell in accordance with an embodiment of the invention. Adapter card **235** receives a cell from network **140** via link interface **335** (step **1000**). Adapter firmware **302** stores the cell in memory unit **200** via peripheral bus interface **315**, peripheral bus **260**, and peripheral bus interface **225** (step **1005**). Adapter card **235** stores the memory address of the cell in the pointer register of Rx register bank **332** (step **1010**). Then, interrupt controller **325** generates an interrupt in CPU **210** (step **1015**).

FIG. **11** is a flow chart of the steps that adapter driver **208** performs when CPU **210** receives an interrupt in accordance with an embodiment of the invention. Adapter driver **208** generates a time-stamp for the current time and stores the time-stamp in memory unit **200** (step **1100**). Adapter driver **208** reads memory address of cell from the pointer register of the Rx register bank **332** (step **1105**). Adapter driver **208** copies the stored time-stamp into the payload of the received cell (step **1110**). Adapter driver **208** then generates a cell-arrival interrupt in TA **410** (step **1115**).

As explained above, when monitoring station **100A** measures the end-to-end QoS in VC **160** based on round-trip transmission time of cells, monitoring station **100B** does not insert QoS monitoring information into the payload of the cells before transmitting the cells back to monitoring station **100A**. However, in an embodiment where monitoring station **100A** measures the end-to-end QoS in VC **160** based on one-way transmission time of cells, monitoring station **100B** must insert a time-stamp in the payload of each cell before transmitting the cell back to monitoring station **100A**. Thus, in such an embodiment, monitoring station **100A** must be synchronized to monitoring station **100B** in order to make accurate and consistent QoS measurements.

Monitoring stations **100A** and **100B** may use various methods for clock synchronization in accordance with an embodiment of the present invention. For example, Global Positioning System (GPS) receivers can periodically synchronize ground systems to a constellation of orbiting satellites to within, for example, 10 ns or better. Alternatively, monitoring stations **100A** and **100B** may use the network time protocol (NTP) to periodically synchronize to Internet time servers. The accuracy depends on the stratum level of the time servers and the method of connection to the time servers. Alternatively, monitoring stations **100A** and **100B** may periodically synchronize to a common server through circuit-switched connections. Each monitoring station could set up a circuit-switched link to the common server, and send a message to the server. The server time-stamps the message and returns the message to the monitoring station. The monitoring station can deduce the propagation delay as half of the round-trip delay, and add the propagation delay to each time-stamp in order to synchronize the monitoring station to the common server clock time.

FIG. **12** is a block diagram of a communications network **1240**, which includes monitoring stations for monitoring a group of virtual circuits in accordance with an embodiment of the invention. As shown, network **1240** comprises monitoring stations **1200A** and **1200B**, source node **1220**, destination node **1230**, and switches **1205**, **1210**, and **1215**, which, for example, may be ATM switches. Specifically,

source node **1220** communicates with destination node **1230** through a group of virtual circuits (VCs) $\mathbf{1250}_1$ through $\mathbf{1250}_N$, which pass through switches **1205, 1210,** and **1215**. VCs $\mathbf{1250}_1$ through $\mathbf{1250}_N$ each have the same path through switches **1205, 1210,** and **1215** and QoS parameters. Monitoring station **1200A** communicates monitoring information with monitoring station **1200B** through VC **1260**, which has the same path and QoS parameters as VCs $\mathbf{1250}_1$ through $\mathbf{1250}_N$. Furthermore, monitoring station **1200A** may comprise the structure of monitoring station **100A** described in FIGS. **2** through **4** above. Accordingly, monitoring station **1200A** may monitor the end-to-end QoS in VCs $\mathbf{1250}_1$ through $\mathbf{1250}_N$ by performing the steps in FIGS. **5** through **11** described above.

In yet another embodiment of the present invention, a single monitoring station can monitor a single virtual circuit (VC) or a group of virtual circuits (VCs) in a communications network **1340**. FIG. **13** illustrates a block diagram of network **1340**, which includes monitoring station **1300**, source node **1320**, destination node **1330**, virtual circuits (VC) **1350** and **1360**, and switches **1305, 1310,** and **1315**, which, for example, may be ATM switches. Source node **1320** communicates with destination node **1330** via VC **1350**. As shown, VCs **1350** and **1360** each pass through switches **1305, 1310,** and **1315**, and have the same path and QoS parameters as each other. Accordingly, monitoring station **1300** monitors the QoS parameters of VC **1350** by monitoring the QoS parameters of VC **1360**. Specifically, monitoring station **1300** may, for example, include a personal computer (PC) with an ATM adapter card, and may operate by performing the steps described in flow charts of FIGS. **5** through **11**.

A network management program (not shown) in monitoring station **1300**, or alternatively in a different computer, establishes VC **1360** with the same path and QoS parameters as VC **1350** by specifying the input port and the output port in each switch **1305, 1310,** and **1310** through which VC **1360** passes. Furthermore, the network management program configures switch **1315** so that VC **1360** loops-back in switch **1315**. With the loop-back configuration, switch **1315** routes the cells that monitoring station **1300** transmits within switch **1315** and transmits the cells back to monitoring station **1300** via switches **1310** and **1305**. Accordingly, monitoring station **1300** can monitor the end-to-end QoS parameters of VC **1350** by determining the QoS parameters of VC **1360**.

While it has been illustrated and described what are at present considered to be preferred embodiments and methods of the present invention, it will be understood by those skilled in the art that various changes and modifications may be made, and equivalents may be substituted for elements thereof without departing from the true scope of the invention.

In addition, many modifications may be made to adapt a particular element, technique or implementation to the teachings of the present invention without departing from the central scope of the invention. Therefore, it is intended that this invention not be limited to the particular embodiments and methods disclosed herein, but that the invention include all embodiments falling within the scope of the appended claims.

What is claimed is:

1. A method for monitoring a first virtual circuit in a network, the first virtual circuit having a path and a first set of quality of service (QoS) parameters, said method comprising the steps, performed by at least one processor, of:

establishing in the network a second virtual circuit comprising the path and the first set of quality of service parameters;

determining a second set of quality of service parameters for the second virtual circuit; and

monitoring the first virtual circuit by comparing one or more of the determined second set of quality of service parameters with one or more of the first set of quality of service parameters.

2. The method of claim **1**, wherein said monitoring step further comprises the step of:

determining a cell transfer delay in the second virtual circuit.

3. The method of claim **1**, wherein said monitoring step further comprises the step of:

determining a cell delay variation in the second virtual circuit.

4. The method of claim **1**, wherein said monitoring step further comprises the step of:

determining a cell loss ratio in the second virtual circuit.

5. The method of claim **1**, wherein said monitoring step further comprises the step of:

determining a maximum cell transfer delay in the second virtual circuit.

6. The method of claim **1**, wherein said monitoring step further comprises the step of:

determining a minimum cell transfer delay in the second virtual circuit.

7. The method of claim **1**, wherein said monitoring step further comprises the step of:

determining an average cell transfer delay in the second virtual circuit.

8. The method of claim **1**, wherein said monitoring step further comprises the steps of:

time-stamping a cell when transmitting the cell on the second virtual circuit; and

time-stamping the cell when receiving the cell on the second virtual circuit.

9. A computer for monitoring a first virtual circuit in a network, the first virtual circuit having a path and a set of quality of service parameters, said computer comprising:

a connection manager for establishing a connection to a second virtual circuit with the path and the first set of quality of service parameters;

a traffic generator for transmitting a plurality of cells on the second virtual circuit; and

a traffic analyzer for monitoring the first virtual circuit by determining a second set of quality of service parameters in the second virtual circuit.

10. The computer of claim **9**, wherein said traffic analyzer further comprises means for comparing the second set of quality of service parameters with the first set of quality of service parameters.

11. The computer of claim **9**, wherein said traffic analyzer further comprises means for determining a cell transfer delay in the second virtual circuit.

12. The computer of claim **9**, wherein said traffic analyzer further comprises means for determining a cell delay variation in the second virtual circuit.

13. The computer of claim **9**, wherein said traffic analyzer further comprises means for determining a cell loss ratio in the second virtual circuit.

14. The computer of claim **9**, wherein said traffic analyzer further comprises means for determining a maximum cell transfer delay in the second virtual circuit.

15. The computer of claim **9**, wherein said traffic analyzer further comprises means for determining a minimum cell transfer delay in the second virtual circuit.

16. The computer of claim 9, wherein said traffic analyzer further comprises means for determining an average cell transfer delay in the second virtual circuit.

17. A method for monitoring a group of virtual circuits in a network, the group of virtual circuits each having a path and a first set of quality of service (QoS) parameters, said method comprising the steps, performed by at least one Processor, of:

establishing in the network a second virtual circuit comprising the path and the first set of quality of service parameters;

determining a second set of quality of service parameters for the second virtual circuit; and

monitoring the group of virtual circuits by comparing one or more of the determined second set of quality of service parameters with one or more of the first set of quality of service parameters.

18. The method of claim 17, wherein said monitoring step further comprises the step of:

determining a cell transfer delay in the second virtual circuit.

19. The method of claim 17, wherein said monitoring step further comprises the step of:

determining a cell delay variation in the second virtual circuit.

20. The method of claim 17, wherein said monitoring step further comprises the step of:

determining a cell loss ratio in the second virtual circuit.

21. The method of claim 17, wherein said monitoring step further comprises the step of:

determining a maximum cell transfer delay in the second virtual circuit.

22. The method of claim 17, wherein said monitoring step further comprises the step of:

determining a minimum cell transfer delay in the second virtual circuit.

23. The method of claim 17, wherein said monitoring step further comprises the step of:

determining an average cell transfer delay in the second virtual circuit.

24. The method of claim 17, wherein said monitoring step further comprises the steps of:

time-stamping a cell when transmitting the cell on the second virtual circuit; and

time-stamping the cell when receiving the cell on the second virtual circuit.

25. A computer-readable medium capable of configuring a computer to perform a method for monitoring a first virtual circuit in a network, the first virtual circuit having a path and a first set of quality of service (QoS) parameters, said method comprising the steps, performed by at least one processor, of:

establishing in the network a second virtual circuit comprising the path and the first set of quality of service parameters;

determining a second set of quality of service parameters for the second virtual circuit; and

monitoring the first virtual circuit by comparing one or more of the determined second set of quality of service parameters with one or more of the first set of quality of service parameters.

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